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Torrefaction and co-torrefaction characterization of hemicellulose, cellulose and lignin as well as torrefaction of some basic constituents in biomass

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ABSTRACT

Torrefaction is a thermal pretreatment process for biomass where raw biomass is heated in the temperatures of 200–300 °C under an inert or nitrogen atmosphere. The main constituents contained in biomass include hemicellulose, cellulose and lignin; therefore, the thermal decomposition characteristics of these constituents play a crucial role in determining the performance of torrefaction of lignocellulosic materials. To gain a fundamental insight into biomass torrefaction, five basic constituents, including hemicellulose, cellulose, lignin, xylan and dextran, were individually torrefied in a thermogravimetry. Two pure materials, xylose and glucose, were torrefied as well for comparison. Three torrefaction temperatures of 230, 260 and 290 °C, corresponding to light, mild and severe torrefactions, were taken into account. The experiments suggested the weight losses of the tested samples could be classified into three groups; they consisted of a weakly active reaction, a moderately active reaction and a strongly active reaction, depending on the natures of the tested materials. Co-torrefactions of the blend of hemicellulose, cellulose and lignin at the three torrefaction temperatures were also examined. The weight losses of the blend were very close to those from the linear superposition of the individual samples, suggesting that no synergistic effect from the co-torrefactions was exhibited.

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1. Introduction

It is accepted that the development of renewable energy nowadays plays a crucial role in reducing the consumption of fossil fuels, greenhouse effect and environmental pollution. At present, solar, wind, geothermal, hydroelectric, tidal and biomass energies have been commercialized, whereas ocean thermal gradient, wave and marine current energies are still in development. In these developed renewable energies, biomass energy or bioenergy accounts for the largest renewable energy in the world [1]. In order to gain energy from biomass, a number of conversion methods have been utilized. For example, direct combustion of biomass has been extensively applied for the purpose of getting heat, power and electricity [2]. Biodiesel produced from some vegetable oils through the process of transesterification has been adopted as an alternative fuel in diesel engines for years [3]. Bioethanol is also generated from some starchy and sucrose-containing materials and has been widely blended with gasoline as fuel for cars [4]. Gasification and pyrolysis can be used to produce synthesis gas (syngas) and biooil from lignocellulosic materials that can be further processed into fuels or used as chemical raw materials [3,5].

When biomass is employed for bioenergy, in some situations, pretreatments of biomass are essential procedures for achieving higher efficiencies of fuel production or consumption. For example, after dewatering and drying, the calorific value of biomass is increased and the combustion efficiency of biomass is enhanced. If biomass is grinded into powder, it can be blended with coal to serve as a pulverized fuel [6]. To convert hemicellulose contained in lignocellulosic biomass to soluble sugars and facilitate the subsequent enzymatic hydrolysis of cellulose, dilute acid pretreatments have been adopted widely for bioethanol production from lignocelluloses [4,7]. In addition to the aforementioned methods, torrefaction of biomass is another notable pretreatment method that can improve the properties of fuels as feedstocks [8].

In general, raw biomass is characterized by high moisture content, relatively low energy density and larger volume, hygroscopic behavior and difficulty of storage. In addition it is difficult to grind into small particles. On account of these characteristics, the potential of raw biomass as an alternative fuel to fossil fuels such as coal is reduced. However, the aforementioned drawbacks of raw biomass can be resolved through the pretreatment of biomass. One of the methods is torrefaction. Torrefaction is a thermal pretreatment process for biomass. In this process, raw biomass is heated in

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the temperature range of 200–300 °C under an inert or nitrogen atmosphere. Reviewing past studies indicates that after experiencing torrefaction the properties of biomass can be improved to a certain extent [8,9]. The improvements in the properties of biomass undergoing torrefaction include: (1) the moisture of raw biomass is reduced markedly [10–12] so that the energy density of the torrefied biomass is increased [13–15]; (2) the O/C ratio in the pretreated fuel is reduced which increases the heating value of the biomass [12,15,16]; (3) the hygroscopic behavior featured by raw biomass is intrinsically converted to be hydrophobic [17] so the torrefied fuel possesses the merits of much lower moisture, and easier storage and delivery; and (4) the ignitability, reactivity and grindability of the fuel is improved to a great extent [16,18,19] so that energy is saved when the processed fuel is ground or pulverized. On account of the altered properties, the usefulness of the biomass as fuel for industrial furnaces is enhanced. For example, it has been reported that torrefaction has a high process efficiency compared to pelletisation and pyrolysis [20] and the technique of torrefaction could be used for wood gasification and syngas production [12].

As a matter of fact, when torrefaction is employed to pretreat biomass, the properties of the torrefied biomass depend highly on the torrefaction temperature. For instance, Yan et al. [15] reported that increasing temperature resulted in decreased mass yield and increased densification of torrefied biomass, and resulted in a solid with increased carbon content, decreased oxygen content and decreased volatiles. Deng et al. [17] also reported that an increase of torrefaction temperature led to a decrease in solid bio-char yield and an increasing yield in volatile matters including liquid and non-condensable gases. Chen and Kuo [8] highlighted the weight losses of four different biomass materials in a light torrefaction environment (240 °C) and a severe torrefaction one (275 °C). They pointed out that hemicellulose contained in the samples was influenced by light torrefaction, whereas cellulose and lignin were hardly affected. In contrast, in severe torrefaction, there was a drastic impact on the depletion of lignocellulosic materials.

It is known that the main constituents contained in biomass include hemicellulose, cellulose and lignin. Therefore, the torrefaction process and performance of a lignocellulosic material depend strongly on the thermal degradation of these constituents. In addition to the aforementioned constituents, xylan and dextran are two other basic components with thermal decompositions that are related to the torrefaction of biomass [13]. Seeing that the torrefactions of the aforementioned constituents has yet to be studied, their thermal degradation characteristics in the environments of torrefaction are explored in the present study to provide a fundamental insight into the torrefaction of lignocellulosic materials. Two pure materials, xylose and glucose, are also studied as a comparison. Co-torrefaction of hemicellulose, cellulose and lignin are carried out as well to evaluate the interaction among the constituents.

2. Experiment

As illustrated above, the five basic constituents of hemicellulose, cellulose, lignin, xylan and dextran as well as two pure materials of xylose and glucose serve as the raw materials to be torrefied. The samples of hemicellulose, xylan, dextran and xylose came from SIGMA where the product numbers were H2125-150KU, X-4252, D9260 and X-1500, respectively. Cellulose was supplied by Alfa Aesar with the product number of A17730. With regard to lignin and glucose, they were obtained from Tokyo Chemical Industrial Co. (L0045) and Panreac Quimica SA (131341), respectively.

The torrefaction processes of the seven materials were carried out in a thermogravimetry (TG, PerkinElmer Diamond TG/DTA). The functions of the TG were to measure and record the weight loss process of a tested material with increasing temperature or time. In the TG, the tested sample was loaded in a crucible where the weight was measured at the frequency of 2 Hz, that is, two sets of data were taken and recorded per second. For all the experimental runs, around 5 mg of sample was used and the heating temperature in the TG ranged from 25 °C to 800 °C. The size of the sample was regulated below 325 mesh (<45 μm) before the materials were tested in the TG. Nitrogen was used as a carrier gas in the TG so that the biomass was pyrolyzed in an inert environment without oxygen. The flow rate of the carrier gas was fixed at 200 cc (25 °C) min^{-1}. When the torrefaction was performed, a temperature program consisting of a dynamic heating period, an isothermal heating period and a dynamic heating period, was applied. Specifically, the temperature of the TG was raised from 25 °C to the torrefaction temperature (i.e. 230, 260 or 290 °C) with the heating rate of 20 °C min^{-1}. Once the TG reached the torrefaction temperature, the biomass was torrefied for 1 h followed by pyrolysis with the heating rate of 20 °C min^{-1} again, until the temperature of 800 °C was reached. From the recorded distribution of the weight loss, one was able to obtain the TGA (thermogravimetric analysis), DTG (derivative thermogravimetric) analysis and DTA (differential thermal analysis). To ensure quality, the TG was periodically calibrated. The experiment under any given condition was usually carried out more than twice. The results were fairly uniform between each run, guaranteeing the measurement quality of the TG. The experiment of co-torrefaction of hemicellulose, cellulose and lignin (weight ratio 1:1:1) at 290 °C for 1 h has been tested three times to confirm the low experimental error. The results indicate that the three curves of DTG almost overlap, revealing that the experimental error is fairly low. As a matter of fact, in the following section, it can also be found that the TG is able to provide an accurate and stable measurement.

3. Results and discussion

In the following discussion, the torrefaction characteristics of the three basic constituents in biomass, hemicellulose, cellulose and lignin, are first studied. To understand the effect of the torrefaction temperature on the weight losses of the materials, three different heating temperatures of 230, 260 and 290 °C with 1 h torrefaction, corresponding to light, mild and severe torrefactions, are adopted to treat the samples. Subsequently, the torrefactions of xylan, dextran, xylose and glucose are discussed. Furthermore, attention is paid to the co-torrefaction of hemicellulose, cellulose and lignin to examine the synergistic effect from the torrefaction of the blend of the three basic constituents.

3.1. Torrefaction characteristics of hemicellulose, cellulose and lignin

The distributions of TGA, DTG and DTA of hemicellulose at the three different torrefaction temperatures are displayed in Fig. 1. As can be seen in Fig. 1a, when the torrefaction temperature of 230 °C is carried out, only 2.74 wt% of hemicellulose is decomposed, implying that the weight loss of hemicellulose from the light torrefaction is slight. Because of this, as shown in Fig. 1b, the peak appeared in the DTG curve is not high. Following the light torrefaction another peak in the DTG curve is seen at around 321 °C. The pyrolysis temperature of the tested hemicellulose is thus identified from the aforementioned temperature. To distinguish the two peaks elicited during and after the light torrefaction, the first and the second peaks are spoken of as the torrefaction peak and the pyrolysis peak, respectively. When the DTA curve shown in Fig. 1c is examined, it is apparent that the torrefaction at 230 °C is characterized by an exothermic process, whereas an endothermic peak is

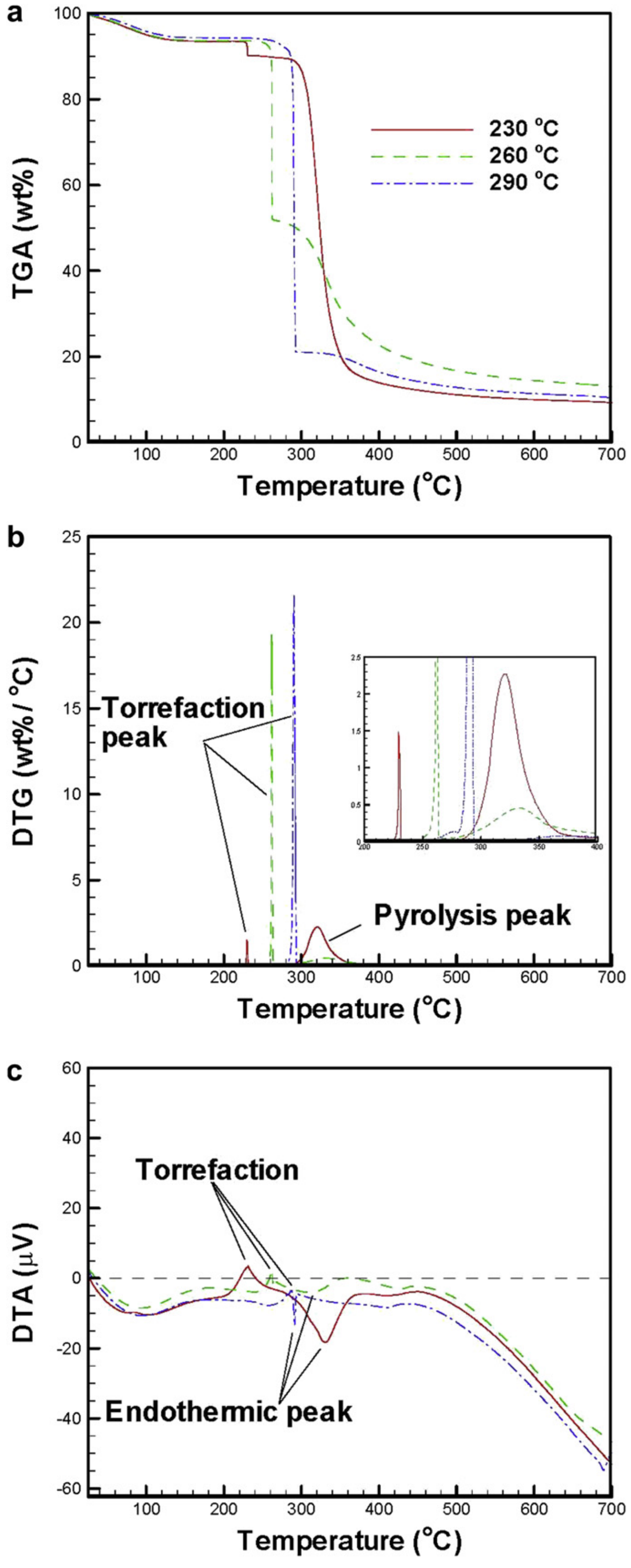

Fig. 1. Distributions of (a) TGA, (b) DTG and (c) DTA of hemicellulose at three different torrefaction temperatures (230, 260 and 290 °C for 1 h).

observed at around the pyrolysis temperature (i.e. 321 °C). It is known that hemicellulose is a polymer with a basic structure of $(C_5H_8O_4)_m$ [7] and m as the degree of polymerization. When the torrefaction proceeds, partial oxygen contained in hemicellulose is consumed for thermal degradation; this leads to the exothermic behavior. However, when the heating temperature of hemicellulose reaches the pyrolysis temperature, the thermal degradation reaction of hemicellulose is intensified and partial oxygen has been depleted from the torrefaction so that extra energy from the surrounding is required, causing an endothermic reaction, as observed. For the torrefaction temperature of 260 °C, 37.98 wt% of hemicellulose disappears. It follows that the mild torrefaction has a profound impact on the thermal degradation of hemicellulose, whereby both the pyrolysis peak and the endothermic peak decay drastically (Fig. 1b and c). With the torrefaction temperature of 290 °C, 58.33 wt% of hemicellulose is consumed from the severe torrefaction and the pyrolysis peak is difficult to be detected in the DTG curve (Fig. 1b). However, a small endothermic peak is observed behind the torrefaction peak (Fig. 1c), revealing the impact of the severe torrefaction on thermal behavior. On the other hand, it is noted that the final residue of the heating process is different slightly. It may be possible to explain this difference for two reasons. The first reason might be due to the intrinsic slight difference in the tested samples each other so that the final residue is different. The second reason might be due to experimental error. However, this error is fairly low, as shown in Fig. 1.

When attention is shifted to cellulose with light torrefaction, Fig. 2a depicts that merely 1.05 wt% of cellulose is depleted. Therefore, the torrefaction peak at 230 °C is relatively small (Fig. 2b). When the temperature of the TG rises after the light torrefaction, the pyrolysis temperature of cellulose can be clearly identified at 361 °C. This pyrolysis temperature is higher than that of hemicellulose which is partially due to the interior of cellulose's crystalline structure [4]. Increasing the torrefaction temperature leads to more cellulose being consumed, the torrefaction peaks are thus higher. Specifically, corresponding to the mild and severe torrefactions, 4.43 and 44.82 wt% of cellulose are consumed, respectively. The basic structure of cellulose can be denoted by $(C_6H_{10}O_5)_m$ [21,22]. Similarly, the pyrolysis peak temperature developed at 361 °C which means that the thermal degradation of cellulose is intensified at around this temperature. From the above observations, it can be seen that cellulose is only mildly affected by the light and mild torrefactions. This reflects that most of the cellulose is retained from the two pretreatments. Consequently, the endothermic peaks shown in Fig. 2c are pronounced. With the execution of severe torrefaction, over 40 wt% of cellulose is torrefied; hence the endothermic peak becomes very small. Fig. 2c suggests that the pyrolysis of cellulose is endothermic intrinsically. This is consistent with the observations of Khezami et al. [23] and Yang et al. [24].

Regarding the torrefaction of lignin, as shown in Fig. 3a, 1.45, 3.12 and 6.97 wt% of lignin are consumed in light, mild and severe torrefactions, respectively. It has been reported that lignin is a phenolic polymer where its structure can be represented by $[C_9H_{10}O_3 \cdot (OCH_3)_{0.9-1.7}]_m$. The polymer essentially encases the polysaccharides of the cell walls, producing a strong and durable composite material resistant to enzymatic attack [4,25]. By virtue of the specific structure of lignin, this constituent resists the pretreatments, regardless of the torrefaction temperature. Lignin is relatively inert to the torrefactions; therefore, the torrefaction peaks of lignin are much smaller than those of hemicellulose and cellulose (Fig. 3b). It is noteworthy that the DTA curves of lignin (Fig. 3c) indicate that, unlike hemicellulose and cellulose, the pyrolysis of lignin is characterized by an exothermic reaction [23,24], regardless of what the torrefaction temperature is.

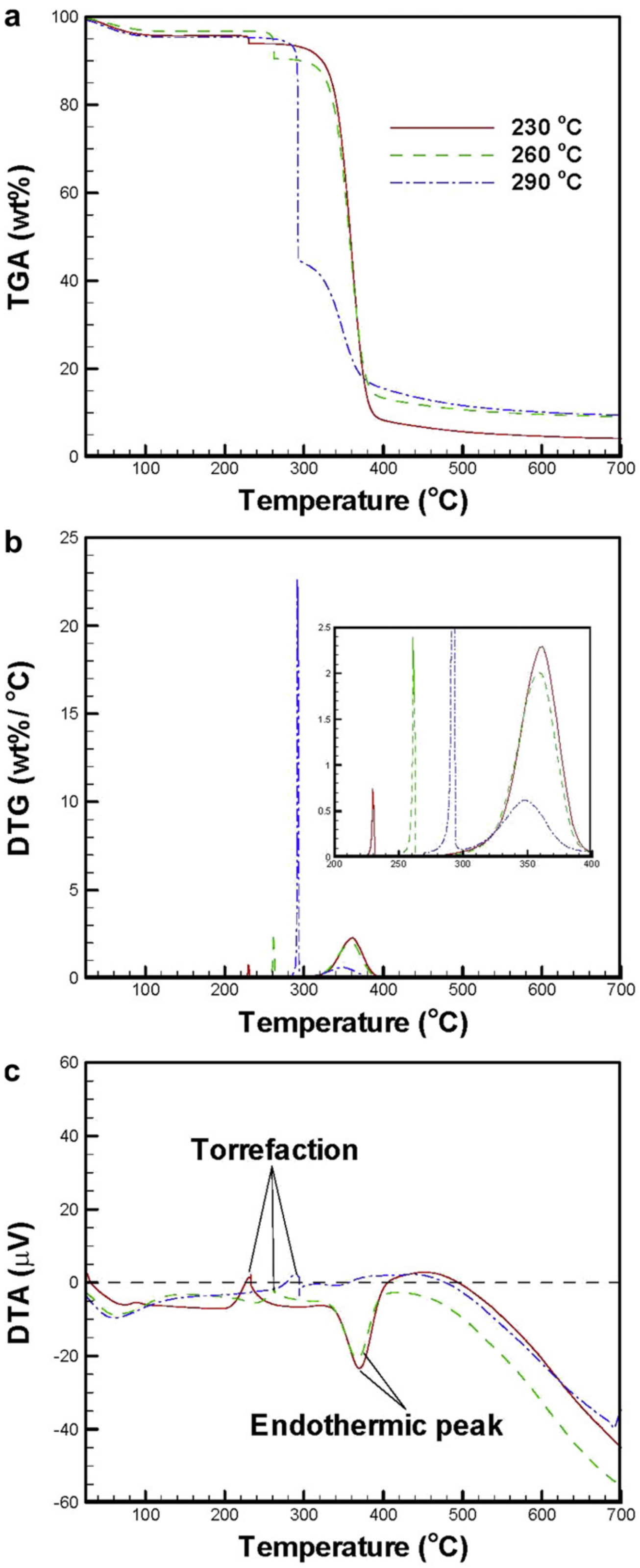

Fig. 2. Distributions of (a) TGA, (b) DTG and (c) DTA of cellulose at three different torrefaction temperatures (230, 260 and 290 °C for 1 h).

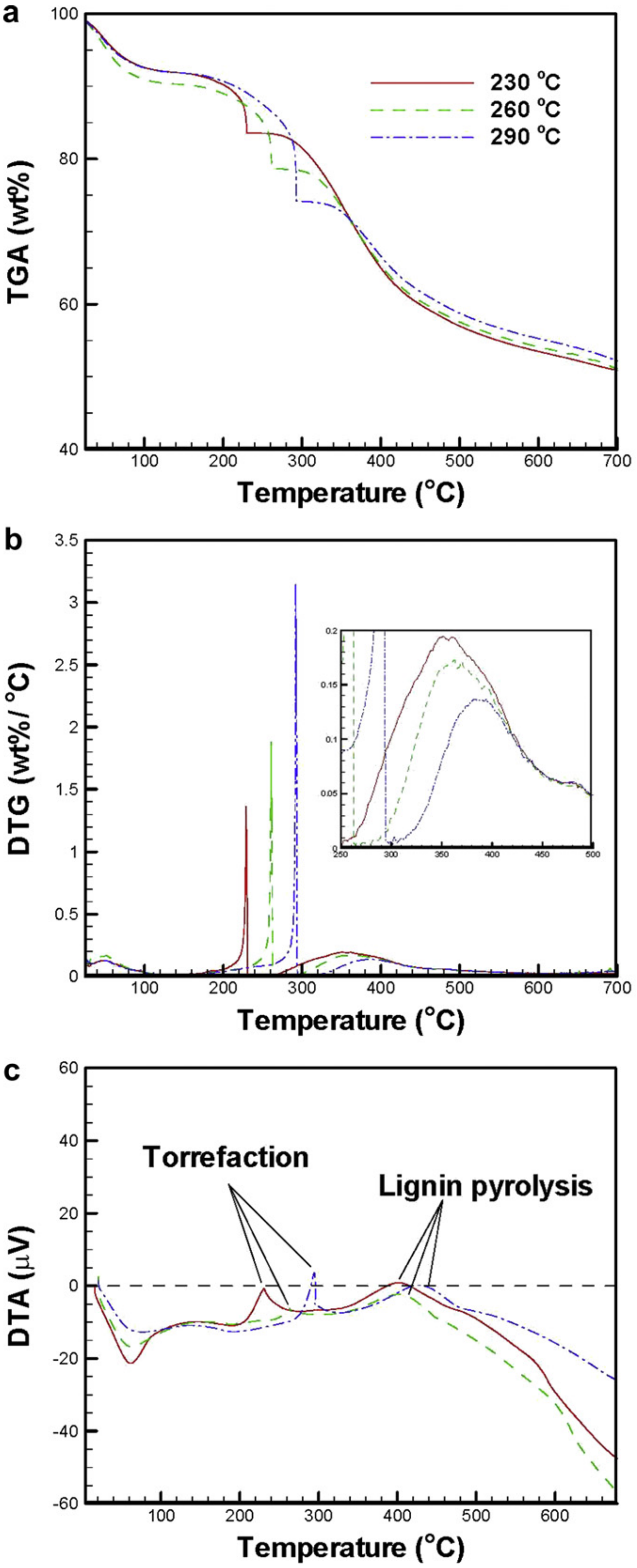

Fig. 3. Distributions of (a) TGA, (b) DTG and (c) DTA of lignin at three different torrefaction temperatures (230, 260 and 290 °C for 1 h).

3.2. Description of torrefaction application

From the above observations, it is apparent that hemicellulose is significantly affected by the torrefaction procedures, even with a torrefaction temperature as low as 230 °C. Cellulose is influenced markedly only when severe torrefaction is applied. In contrast, the torrefaction procedures have almost no impact on lignin whether light, mild or severe torrefaction is employed. Accordingly, it is clear that the characteristics of thermal degradation of the three basic constituents of biomass are different from one another. Furthermore, from the viewpoint of practical applications of torrefaction, if the light torrefaction (230 °C) is applied for the pretreatment of biomass, its function will be to remove moisture and light volatiles from the biomass. Therefore, it is inferred that the heating value of the torrefied biomass is improved to a small extent. If the mild torrefaction (260 °C) is performed, the heating value of torrefied biomass is mainly contributed by cellulose because, in general, the content of cellulose is much higher than that of lignin and they both are locked in biomass from the mild torrefaction. Alternatively, if biomass is pretreated using the severe torrefaction (290 °C), the role played by lignin on energy contribution might be more important than that of cellulose, resulting from a large portion of cellulose being consumed in the severe torrefaction. It should be pointed out that hemicellulose and cellulose are the main constituents in biomass. In light of the drastic consumptions of hemicellulose and cellulose from the severe torrefaction, this route is not recommended for the pretreatment of biomass.

3.3. Torrefaction characteristics of xylan, dextran, xylose and glucose

It is known that hemicellulose comprises xylan [13,25] and the basic unit of xylan is xylose. Meanwhile, dextran contains a substantial number of α-1,6 glycosidic linkages together with various proportions of α-1,2, 1,3 and 1,4 glycosidic linkages [26]. Since cellulose is a homopolysaccharide composed of β-D-glucopyranose units linked together by β-1,4 glycosidic bonds [7], the torrefaction of dextran may provide a reference for recognizing the thermal degradation of cellulose. For these reasons, the distributions of TGA, DTG and DTA of xylan, dextran, xylose and glucose are displayed from Fig. 4 to Fig. 7 to provide a comprehensive insight into the torrefaction of biomass.

Regarding xylan, it is of interest that part of the xylan has been depleted prior to torrefaction, no matter of what kind of torrefaction process is performed. This confirms that xylan is an active constituent in a heating environment [13]. The weight losses of xylan during the light, mild and severe torrefactions are 14.16, 17.10 and 3.94 wt%, respectively (Fig. 4a). It is noted that the pyrolysis peak behind the light torrefaction develops at 302 °C and the peak moves toward the high temperature region as the torrefaction temperature is increased (Fig. 4b). This reveals that the property of xylan is changed to a certain extent when torrefactions are employed. Moreover, in view of the active feature of xylan, the weight loss of xylan in the course of the severe torrefaction is low (i.e. 3.94 wt%), resulting from a large portion of xylan that is consumed before the severe torrefaction occurs. From the DTA distributions shown in Fig. 4c, a certain amount of heat is released in the course of torrefaction so that three peaks in the DTA curves are exhibited at 230, 260 and 290 °C, respectively. Meanwhile, it should be addressed that the pyrolysis peak following the light torrefaction are relatively pronounced (Fig. 4b) compared to those of the mild and severe torrefactions; this induces an endothermic peak in the former (Fig. 4c) whereas this behavior is not observed in the mild and severe torrefactions.

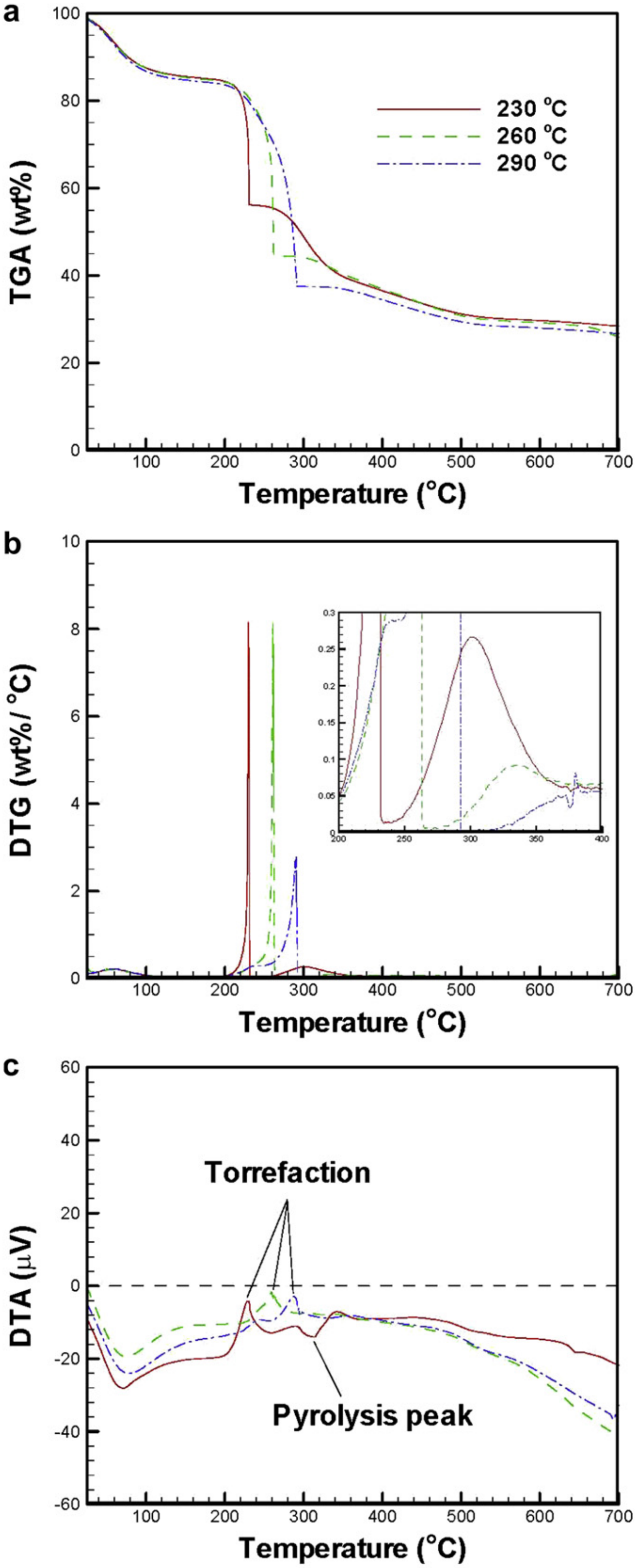

Fig. 4. Distributions of (a) TGA, (b) DTG and (c) DTA of xylan at three different torrefaction temperatures (230, 260 and 290 °C for 1 h).

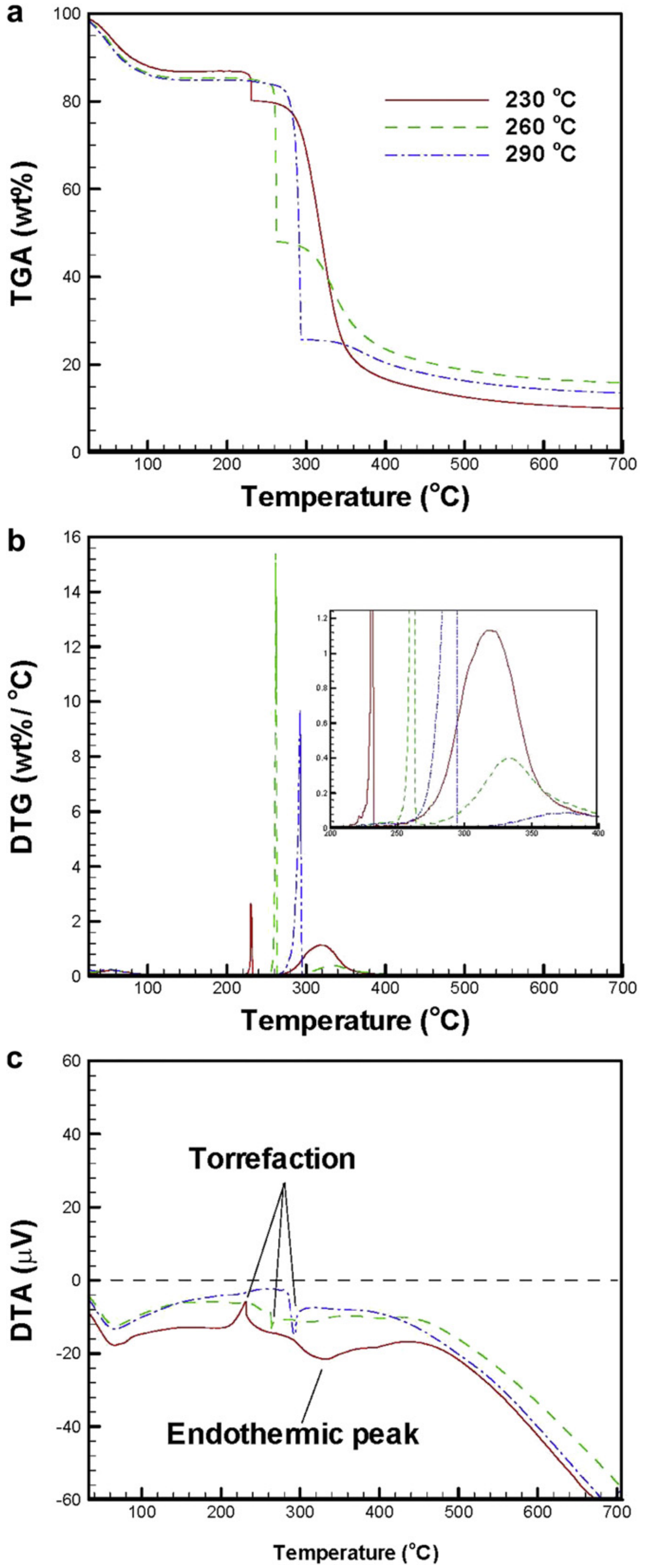

Fig. 5. Distributions of (a) TGA, (b) DTG and (c) DTA of dextran at three different torrefaction temperatures (230, 260 and 290 °C for 1 h).

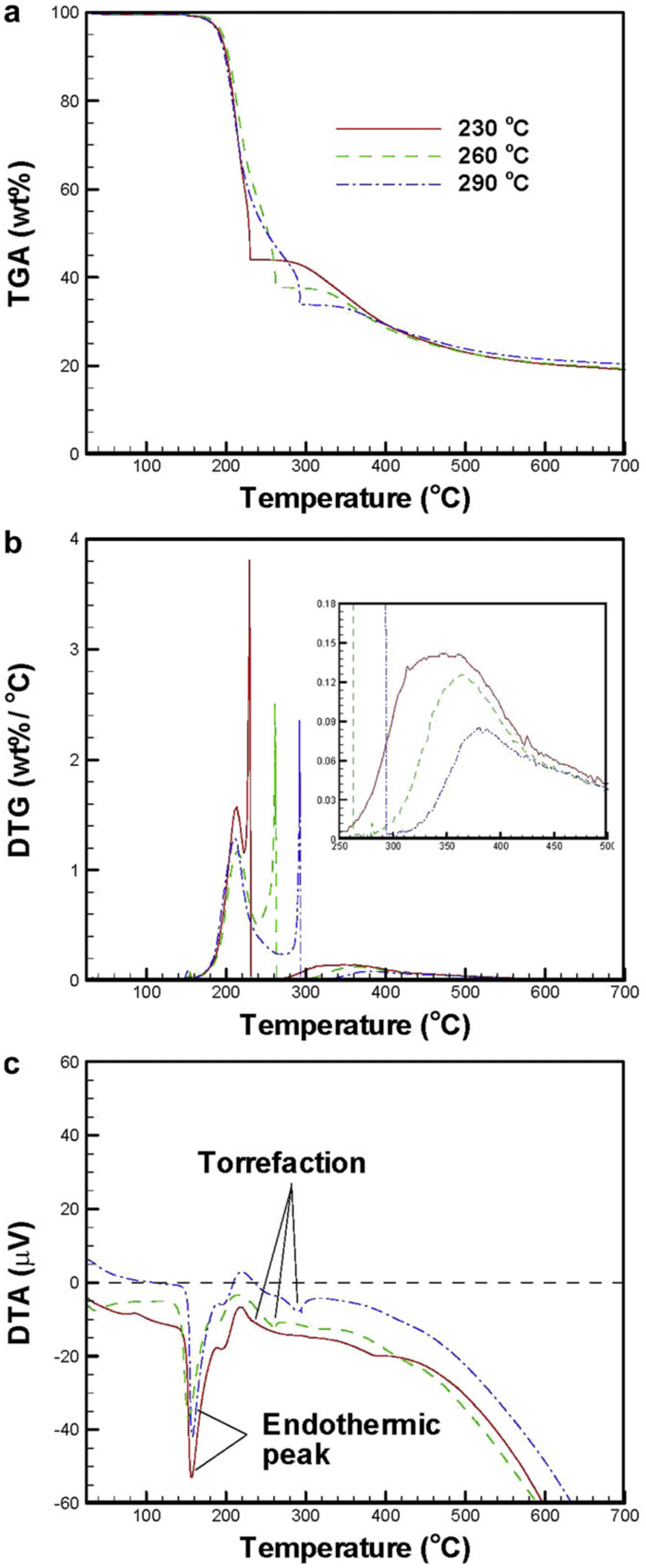

Fig. 6. Distributions of (a) TGA, (b) DTG and (c) DTA of xylose at three different torrefaction temperatures (230, 260 and 290 °C for 1 h).

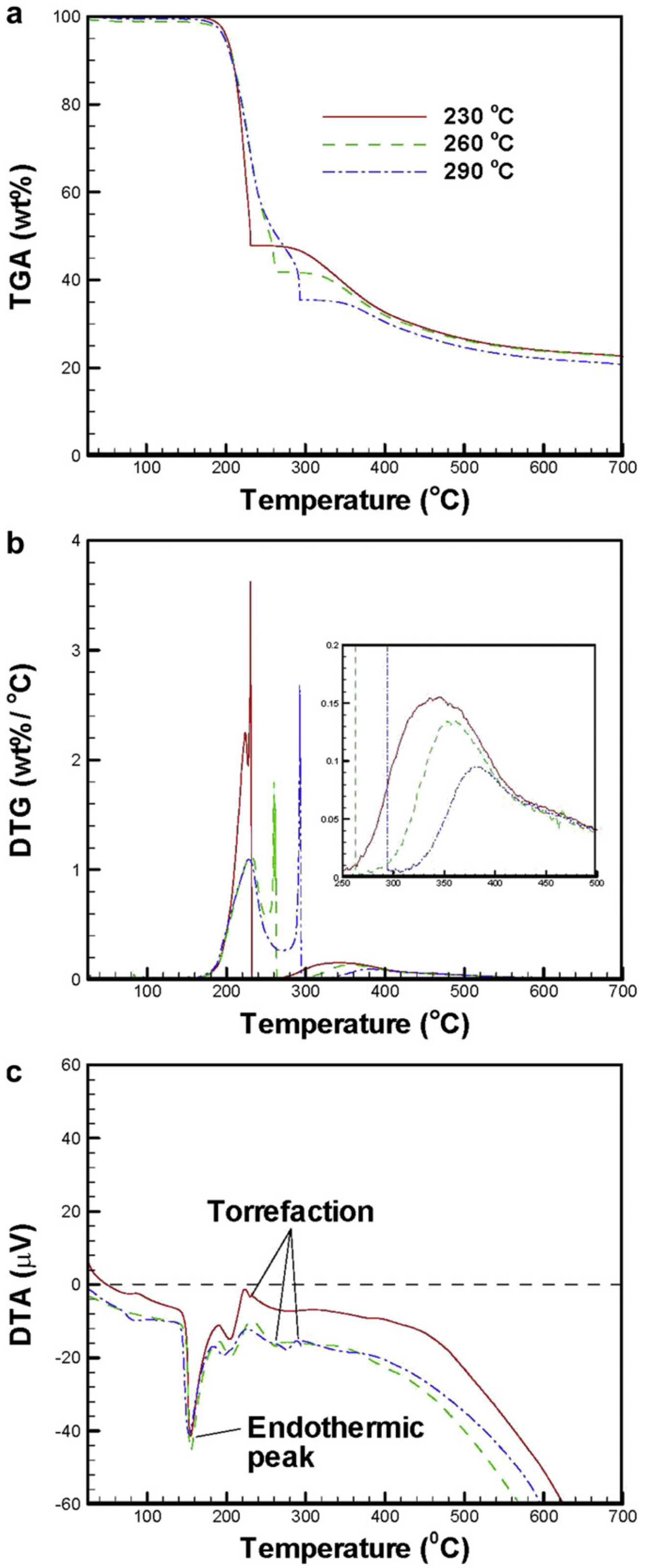

Fig. 7. Distributions of (a) TGA, (b) DTG and (c) DTA of glucose at three different torrefaction temperatures (230, 260 and 290 °C for 1 h).

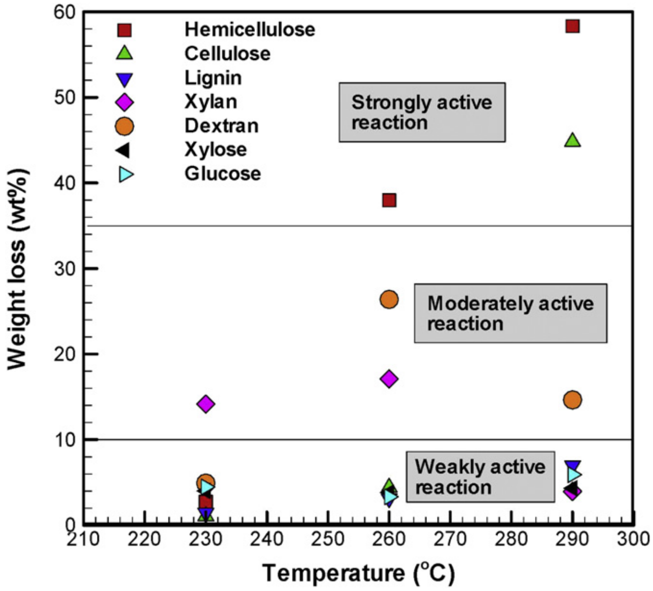

Fig. 8. Weight loss distributions of the tested samples during three different torrefaction temperatures (230, 260 and 290 °C for 1 h).

When the light torrefaction is applied, its impact on dextran is slight (Fig. 5a) since only 4.92 wt% of dextran is consumed. In consequence, the TGA curve at 230 °C is relatively slight (Fig. 5b) and a pyrolysis peak is exhibited at 320 °C. When the curve of DTA is examined (Fig. 5c), the peaks of torrefaction and pyrolysis can be clearly identified. Once the mild torrefaction is employed, the weight loss of dextran becomes remarkable (26.39 wt%). Similar to xylan shown in Fig. 4b, before the temperature reaches 290 °C, part of the dextran has been decomposed. In consequence, only 14.66 wt% of weight loss is observed and the severe torrefaction peak is smaller than the mild one (Fig. 5b). By virtue of the consumption of dextran in the courses of mild and severe torrefactions, the pyrolysis peaks substantially wither (Fig. 5b) and the endothermic peaks cannot be identified from the DTA curves (Fig. 5c).

As far as xylose and glucose are concerned, as shown in Figs. 6a and 7a, before the heating temperature reaches the torrefaction environments, large amounts of xylose and glucose have been pyrolyzed. As a result, unlike the previous five materials, the pyrolysis peaks of xylose and glucose are excited in front of the torrefaction ones, as shown in Figs. 6b and 7b. The pyrolysis peaks of both the xylose and glucose develop at around 210 and 225 °C, respectively. Therefore, when the samples are torrefied, the extents of weight loss of the samples are always less than 6 wt%. In examining the DTA curves of the samples shown in Figs. 6c and 7c,

Table 1
Summary of torrefaction sensitivity of the tested materials.

	230°C	260°C	290°C
Hemicellulose	△	○	○
Cellulose	△	△	○
Lignin	△	△	△
Xylan	□	△	△
Dextran	△	□	□
Xylose	△	△	△
Glucose	△	△	△

△: weakly active reaction (weight loss < 10 wt%).
□: moderately active reaction (10 wt% ≤ weight loss ≤ 35 wt%).
○: strongly active reaction (weight loss > 35 wt%).

it is worth noting that the curves feature three endothermic peaks. The first and the second endothermic peaks are identified approximately at 160 and 200 °C, respectively, resulting from the inherent reactions of xylose and glucose; the third peaks are due to the torrefaction reactions. However, the torrefaction peaks of glucose are very small so that they are almost imperceptible.

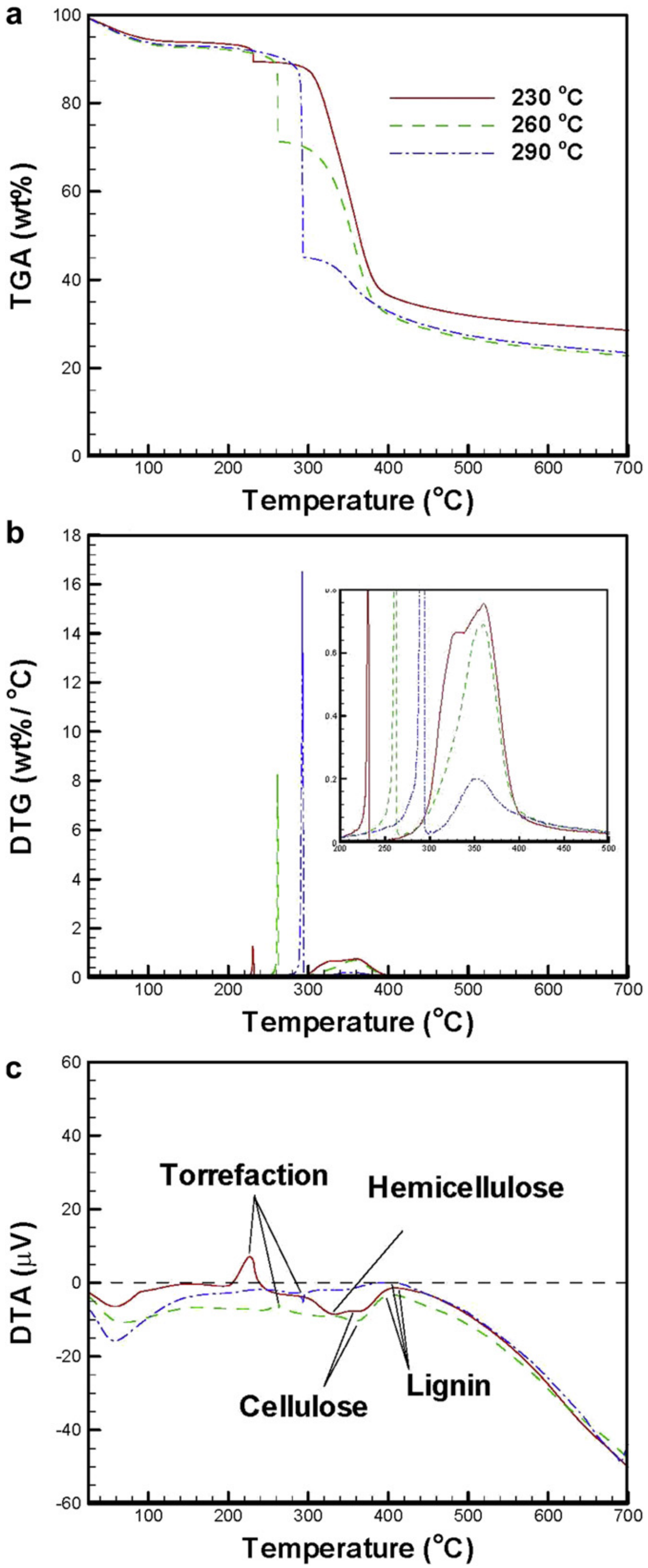

Fig. 9. Distributions of (a) TGA, (b) DTG and (c) DTA from co-torrefaction of hemicellulose, cellulose and lignin blend at three different torrefaction temperatures (230, 260 and 290 °C for 1 h and hemicellulose: cellulose: lignin = 1:1:1).

3.4. *Torrefaction sensitivity of the tested materials*

Subsequently, the weight loss profiles of the seven materials from the three torrefactions in accordance with the preceding measurements are summarized in Fig. 8, whereas the torrefaction sensitivities of the tested samples are listed in Table 1. In light of the results shown in Fig. 8 and Table 1, the weight loss of the materials at various torrefaction conditions can be classified into three different types; they are the weakly active reaction (weight loss $<$ 10 wt%), moderately active reaction (10 wt% $\leq$ weight loss $\leq$ 35 wt%) and strongly active reaction (weight loss $>$ 35 wt%). Evidently, when the light torrefaction is performed, all the materials undergo weakly active reactions, except for xylan. With the conditions of mild and severe torrefactions, hemicellulose and dextran are individually characterized by strongly and moderately active reactions, respectively, whereas cellulose is characterized by moderately and strongly active reactions when the mild and severe torrefactions are carried out, respectively. On the other hand, seeing that the weight losses of lignin, xylose and glucose are always lower than 10% for all the torrefaction processes, these three materials have weakly active reactions in the environments of torrefaction. However, it should be emphasized that the weak reaction of lignin is intrinsically different from those of xylose and glucose. The former is attributed to lignin's high resistance to thermal degradation in the torrefaction processes, whereas the latter is owing to the active nature of xylose and glucose before the torrefactions commence.

3.5. *Co-torrefaction of hemicellulose, cellulose and lignin*

Co-torrefaction behavior of the blend of hemicellulose, cellulose and lignin is examined in Fig. 9 where the weight percentages of the

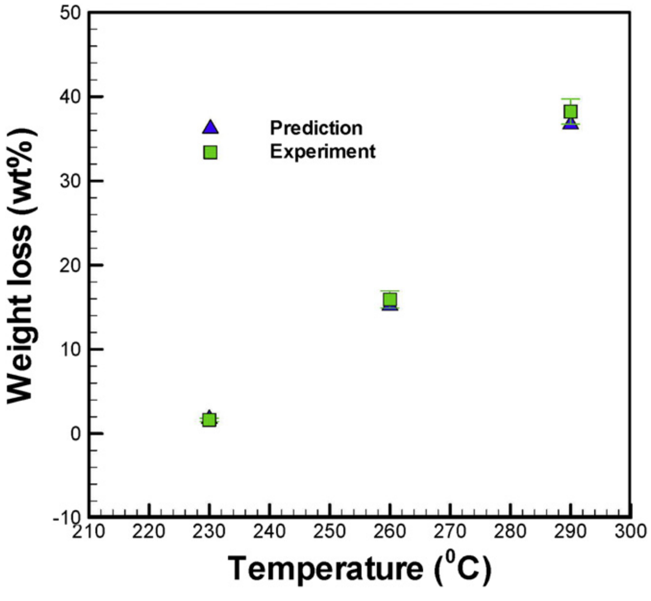

Fig. 10. A comparison of weight loss from co-torrefaction of hemicellulose, cellulose and lignin blend and linear superposition of individual torrefactions of hemicellulose, cellulose and lignin at three different torrefaction temperatures (230, 260 and 290 °C for 1 h and hemicellulose: cellulose: lignin = 1:1:1).

three constituents are controlled at the equivalent ratio (i.e. 1/3 each). It is not surprising that the weight loss of the mixture from the light torrefaction is fairly small (Fig. 9a). Hence, the pyrolysis peaks of hemicellulose and cellulose are clearly identified from the DTG curve (Fig. 9b). The weight drop of the blend with the mild torrefactions depends on the reaction of hemicellulose and, therefore, its pyrolysis peak disappears. The weight loss of the blend with the severe torrefaction is mainly due to reactions of hemicellulose and cellulose. The pyrolysis peak behind the torrefaction peak thus is markedly lower. Upon inspection of the DTA curves of torrefaction (Fig. 9c), the thermal features of hemicellulose, cellulose and lignin can be figured out from the three torrefactions. Based on the above measurements, a comparison of weight loss between the co-torrefaction of the mixture and the linear superposition of the individual constituents are demonstrated in Fig. 10. As a whole, the measured results are very close to the predicted ones, suggesting that no synergistic effect [6] of co-torrefaction is exhibited.

4. Conclusions

Torrefactions of the five basic constituents (i.e. hemicellulose, cellulose, lignin, xylan and dextran) and two pure materials (i.e. xylose and glucose) have been performed to investigate the thermal degradation characteristics of the tested samples. From the performances of various torrefaction temperatures (i.e. 230, 260 and 290 °C), useful insights into the pretreatment of biomass through torrefactions have been obtained. As a whole, the torrefaction with 230 °C just released some moisture and light volatiles from the tested samples; it is thus recognized that this procedure had a relatively slight impact in improving the properties of biomass. The torrefaction with 260 °C caused a certain amount of hemicellulose pyrolyzed, whereas cellulose and lignin were only barely affected. It was expected that the properties and heating value of the torrefied biomass could be intensified to a great extent. When biomass underwent the torrefaction with 290 °C, large amounts of hemicellulose and cellulose were destroyed. It was thus ascertained that this pretreatment procedure disadvantaged the torrefied biomass, as a consequence of a large portion of mass being consumed. Accordingly, from the fiber (i.e. hemicelluloses, cellulose and lignin) analyses of biomass, one was able to infer the influence of torrefaction temperature on biomass. The blend of the three constituents was also torrefied at the three torrefaction temperatures to evaluate the synergistic effect of co-torrefaction. As a result, no interaction among the torrefactions of the three constituents was exhibited. Hence, it was concluded that the weight loss of biomass from a torrefaction could be predicted from the linear superposition of the weight losses of the individual constituents.

Acknowledgments

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